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## Cover Page Footnote

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# Investigation of The Effect of Corundum Layer on The Heat Transfer of SiC Slab

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**Abstract.** Aluminum is the most widely used metal in industry. Aluminum smelting is one of the important steps that needs to be carried out to produce products made of aluminum metal with good quality. In the process of smelting aluminum there are several problems that occur, one of which is the growth of corundum in SiC refractories which affects the quality of aluminum melt and the durability of SiC refractories. This research was conducted to see the heat transfer in SiC and the effect of the presence of Corundum on heat transfer. This research was carried out by simulation using COMSOL Multiphysics to see the distribution of heat and the resulting temperature. The simulation is carried out in two dimensions geometry of a SiC slab and a layer of corundum added. From the simulations carried out for two conditions, namely SiC without corundum and SiC with corundum, it was found that the presence of corundum would inhibit the heat transfer process on SiC Slab.

Keyword: Corundum, SiC, simulation, heat transfer

## INTRODUCTION

Aluminum is a lightweight metal with corrosion-resistant properties, so it is most widely used in various industrial sectors [1,2]. One of the industry's most commonly used manufacturing processes is aluminum die casting [3]. In the die-casting process, aluminum is melted beyond its melting point using a furnace. In cast aluminum housings, the behavior of the treatment furnace's refractory lining significantly impacts the metal processing efficiency and the quality of hot metal production [4]. In the aluminum melting process in the furnace, there are various problems, including the growth of a layer of corundum ($Al_2O_3$) that arises due to the contact between silica and aluminum on the inner surface of the furnace [5]. Corundum growth in the refractory layer is usually caused by the penetration of molten aluminum, which reacts with oxygen gas contained in the pores of the refractory made of silica and iron oxide [6,7,8]. Corundum growth in the refractory layer of the reverberatory furnace causes the efficiency of the furnace to decrease due to the reduction in the thickness of the refractory layer, causing hot spots [9].

Corundum is the mineral name for $Al_2O_3$ in this manuscript, a mixture of $Al_2O_3$ with unreacted refractory pieces plus Si and Al. Corundum is challenging to remove because it firmly attaches itself to the refractory by filling its porosity [10]. Corundum formation affects two critical destructive mechanisms, which reduce the lifespan of refractories, chemical attack (corundum growth or corrosion from flux addition) and mechanical damage (from ingot loading, cleaning practices, or thermal shock). There are two types of corundum: internal and external. Internal corundum exists where the molten alloy penetrates the refractory and reacts with the refractory oxides and external corundum at the bellyband, which induces maximum corrosion to form corundum caused by alloy penetration into the refractories, which is initiated by capillary action, and in the presence of atmospheric oxygen [11]. Corundum has a higher thermal conductivity than refractories, so the thermal efficiency of the retaining furnace is directly proportional to the volume of the solid corundum layer. Thus, energy is lost through the refractory layer. To maintain the furnace temperature, additional heating is required. Therefore, the process has a more negative impact on energy costs [12,13].

Corundum growth when liquid aluminum reacts with free silica in refractories and causing severe distortion and cracking of the lining. The study conducted by A. Wynn et al found that corundum resistance begins to degrade as firing temperature increase and in particular, corundum growth is often start at hot spots in the furnace, where temperature can be measured in excess of 1000ºC [5]. Another study by E.G. Davis found that molten metal penetrates the porous refractory and when exposed to an oxidizing atmosphere the corundum develops. He also found that presence magnesium in the alloy metal affect the rate of corundum growth and corundum didn't not develop on the phosphate-bonded alumina or spinel refractories [8].

This paper aims to observe the growth of corundum in the refractory furnace and to measure the effect of the corundum layer on heat transfer in the furnace during aluminum melting. For observations and measurements of heat transfer due to corundum growth, simulation was carried out with COMSOL Multiphysics.

## MATERIAL AND METHODE

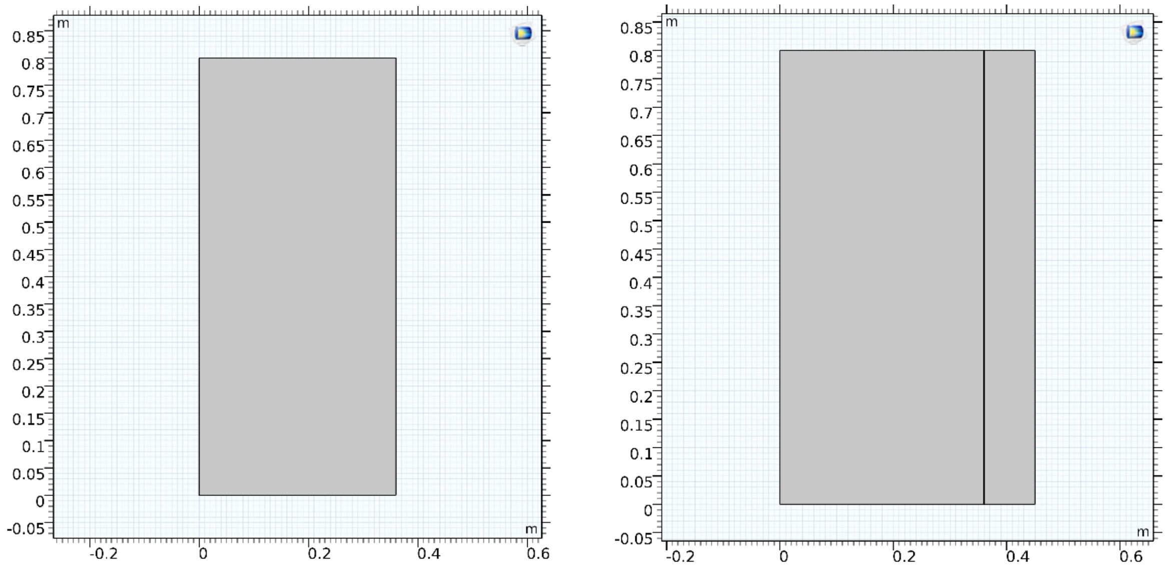
In this study, simulation was performed with COMSOL Multiphysics commercial software which compatible with modelling experimental application in a software environment. Several modules introduced by COMSOL such as heat transfer, AC/DC, acoustics, electrochemistry, fluid flow, optics, plasma, semiconductor, structural mechanics and many more. For this case, to investigate heat transfer in SiC slab using heat transfer module in solid. The module was performed in 2D geometry and time dependent simulation. The time dependent was set for 120 minute or 2 hours. The simulation generates temperature changes along thickness of SiC and corundum during those time.

The simulation was carried out by observing the heat transfer on SiC with a thickness of 36 cm and then simulating SiC with the same thickness which has corundum with a thickness of about 9 cm. Simulation of heat transfer between two solid materials which represent a wall of refractory with corundum for aluminum melting.

### 2D Geometry and Meshing Analysis

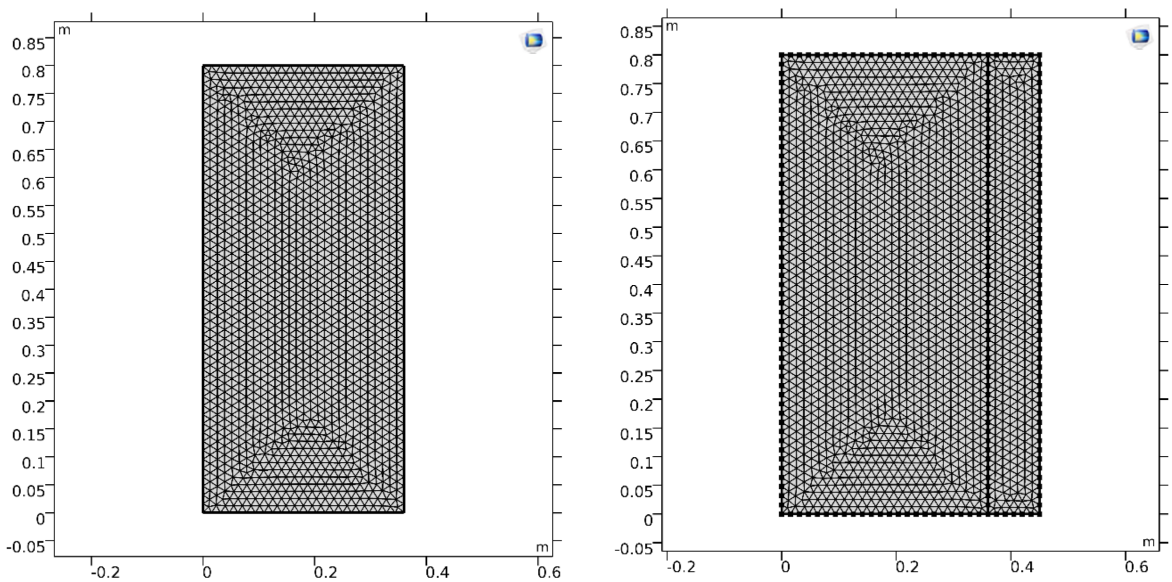
The simulation step starts with making the geometry. The geometry used is 2D geometry in form of rectangle which represent slab thickness of SiC and corundum. The configuration of rectangle 1 which represent a SiC slab having a height x width of 36 cm x 80 cm. The second simulation was done by SiC slab are placed side by side with other rectangle which different material types to represent refractory conditions with corundum. The dimension configuration of rectangle 2 which is corundum $Al_2O_3$ having height x width of 80 cm x 9 cm. The geometry is shown in Fig 1.

Meshing analysis has crucial effect on any simulation study. In COMSOL; there are two different meshing types: i) user controlled, ii) physics-controlled. While physical controlled option enables automatic mesh construction, user-controlled mesh allows manual element size adjustment. This study using physical controlled mesh because of default mesh and simple geometry. There are two mesh type normally used in COMSOL Multiphysics simulation which are tetrahedral element type and triangular element type. The tetrahedral element type is the basic and simplest one among others for most "COMSOL Multiphysics" applications. The triangular element type can be used in some special circumstances. Since mesh algorithms generally need more input for this element type, it cannot be used for every geometry. While triangular have high aspect ratios, the aspect ratio is limited to unity for tetrahedral mesh elements. In those cases where the analysis results are not crucial, it is favorable to use a triangular element type. The mesh construction of the geometry is shown in Fig 2. The following mesh parameters used in this study are tetrahedral mesh type, extra fine element size, 2858 mesh element number for SiC only and 3572 mesh element number for SiC and corundum.




(a) (b)

**FIGURE 1.** (a) Geometry of SiC slab, (b) Geometry of SiC slab with corundum




(a) (b)

**FIGURE 2.** (a) Mesh result of SiC slab, (b) Mesh result of SiC slab with corundum

## Material, Boundary and Condition Parameter

Thermal and boundary conditions were assigned to solve the equations in the heat transfer. Furthermore, the parameters for the heat transfer module are given in the form of a temperature on the SiC side of 800ºC or 1073 K, where the ambient temperature is 30ºC or 303 K are shown in Fig 3. The heat transfer process used in this module involves conduction mechanism. Heat transfer by conduction occurs via the transfer of energy from atom to atom (or molecule to molecule) in a material. Atoms vibrate faster in higher temperature as they possess more energy. This energy will be passed to the adjacent atoms having lower energy.

For one dimensional heat conduction equation Fourier's law of heat conduction [14]:

$$q = -k\frac{\partial T}{\partial x} \tag{1}$$

Where q is heat flux vector in W/m$^2$, k is thermal conductivity in W/ (m. K), T is temperature in K. In general form in Cartesian coordinates, of the heat diffusion equation [14]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho C_p \frac{\partial T}{\partial t} \tag{2}$$

For one dimensional condition, heat transfer only on x direction, the equation can be simplified as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + q = \rho C_p \frac{\partial T}{\partial t} \tag{3}$$

Assumptions for this simulation one dimensional conduction in the x direction, isotropic medium with constant properties and uniform internal heat generation. ρ is solid density in kg/m3 in which k is the thermal conductivity in W/ (m. K), T is the temperature in K, and Cp is the solid specific heat capacity in J/kg. K. The properties for SiC and corundum, were chosen from the built-in material library.

As mention before there are two kind of material using in this simulation which are SiC and Corundum ($Al_2O_3$). Thermal parameter of materials is listed in Table 1.

**TABLE 1.** Thermal Parameter of Material

| **Material** | **Melting Point (K)** | $\rho\ (kg/m^3)$ | $C_p\ (\frac{J}{kg.K})$ | $k\ (\frac{W.}{(m.}K))$ |
|---|---|---|---|---|
| SiC (Silicon Carbide Polycrystalline) | 3100 | 3160 | 675 | 490 |
| Corundum ($Al_2O_3$) (Aluminum Oxide Polycrystalline) | 2323 | 3970 | 765 | 36 |

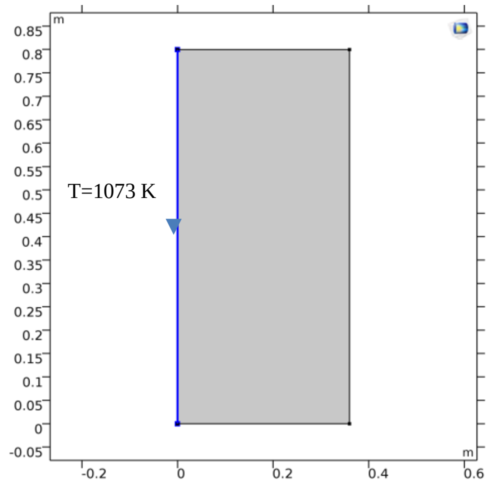



**FIGURE 3.** Boundary condition

## RESULT AND DISCUSSION

The result of first simulation is shown in Fig 4. The color change indicates the temperature distribution along the SiC slab. The temperature distribution show heat transfer distribution. The color range used is blue for the lowest temperature (303 K) and red for the highest temperature (1073 K). It can be seen in the picture that there is a color change in the geometry which indicates that heat transfer occurs over time. The observed distribution was at 5 min and 120 min. Figure 4 (a) show that at in 5 min heat begins to distribute into the SiC thickness and Fig 4 (b) show that in 120 min the heat distribution is almost evenly distributed throughout the SiC surface as shown by the red image which is almost evenly distributed.

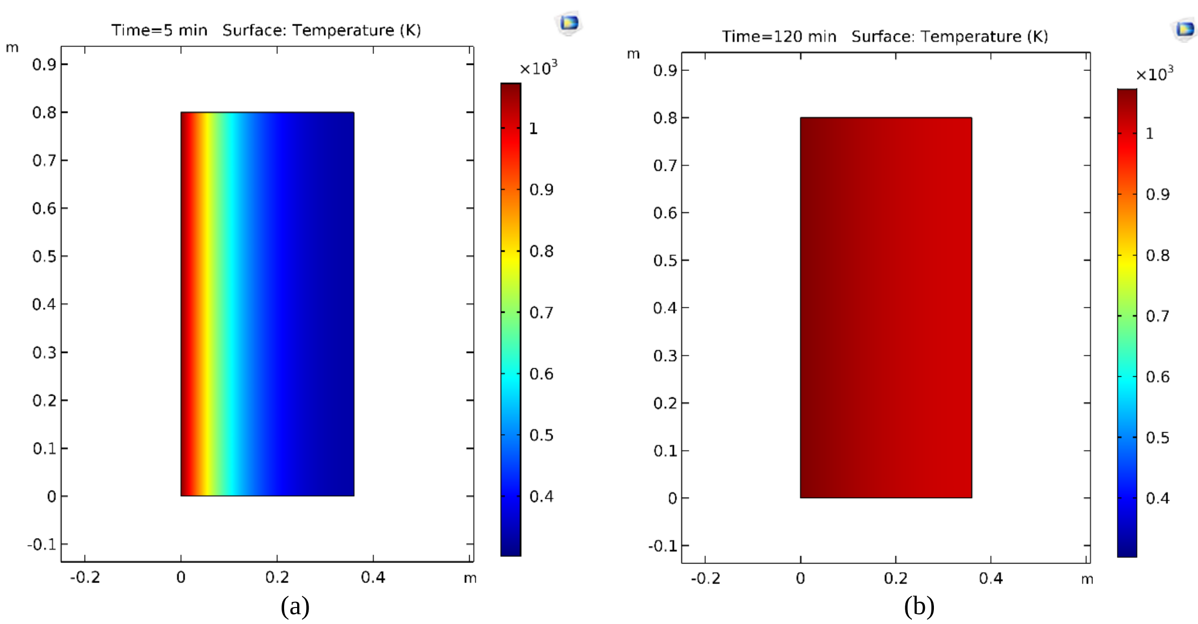



**FIGURE 4.** Temperature distribution of SiC at (a) 5 min, (b) 120 min

The value of the temperature distribution along SiC thickness for 120 min is shown on the graph in Fig 5. The y-axis show temperature values (K) and x-axis show SiC thickness (m). The graph shows that in the 5 min heat transfer has occurred up to the SiC thickness (x=36 cm) where there is an increasing in temperature from 303K to 334 K, as time increases the amount of heat at the point of thickness 36 cm increases and reaches a temperature of 1013 K in 120 minutes as shown in Fig 6 (a). This shows that for 120 min, the heat transfer is still sufficient to be used as a heat source for aluminum melting process [15]. When adding up to 240 min (3 hours) of time, the SiC thickness of 36 cm is able to reach a temperature of 1057.74 K.

The second simulation is doing by adding a corundum layer after SiC side. The purpose of this simulation to observe a change in heat transfer that maybe happen. At the right side of SiC slab added with corundum material. The thickness of corundum is a quarter thickness of SiC which is 9 cm. The simulation results are shown in Fig 7. The results of the temperature distribution for these conditions are shown in Fig 8. Simulation result shows color change along SiC and corundum layer. Color change indicate distribution of heat transfer and same as above, blue color show lowest temperature 303 K and red color show highest temperature 1073 K. In this case, simulation result for 5 min and 120 min was observed.

The simulation results show a significant difference in color at 120 min. In 5 min there is no significant difference in heat transfer between simulation result of SiC and SiC with corundum, which means that the distribution of heat transfer during 5 min in both SiC conditions without corundum and with corundum almost has the same heat distribution. The temperature distribution graphs for the SiC and corundum geometries are shown in Fig 8. It is seen that the presence of corundum reduces the heat transfer that will be provided to melt aluminum. In the Fig 9 showing the temperature change at 120 min, it is observed that the temperature at the corundum tip is 823 K, which is not sufficient to melt aluminum.

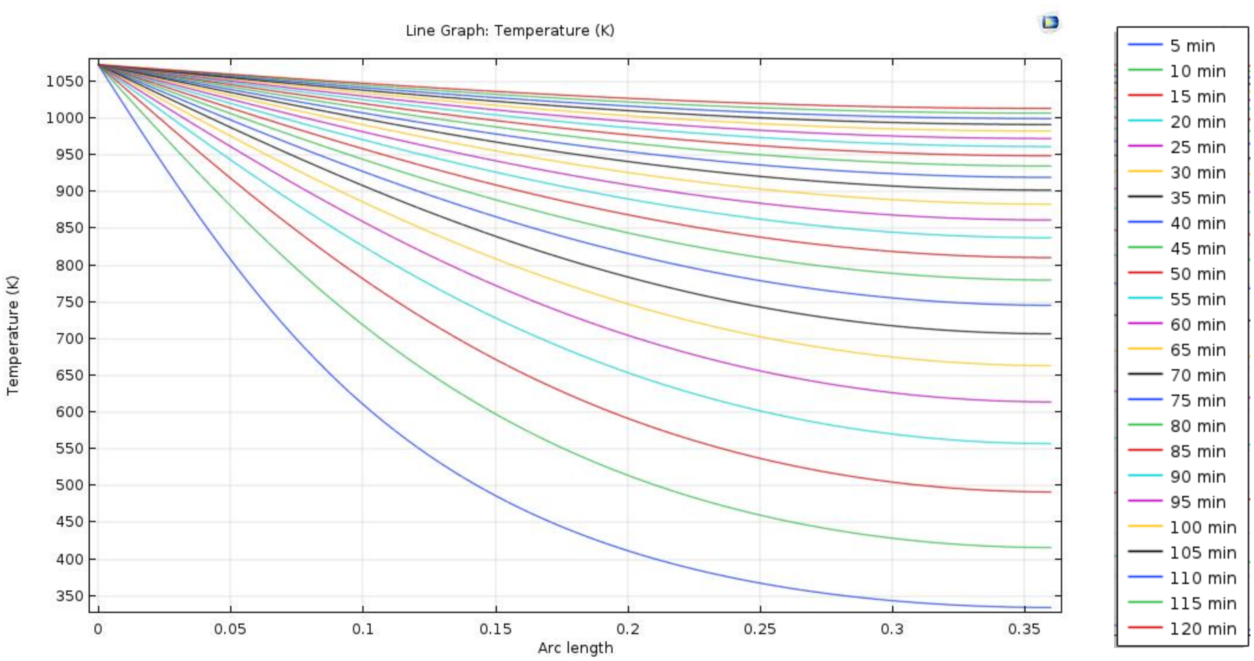
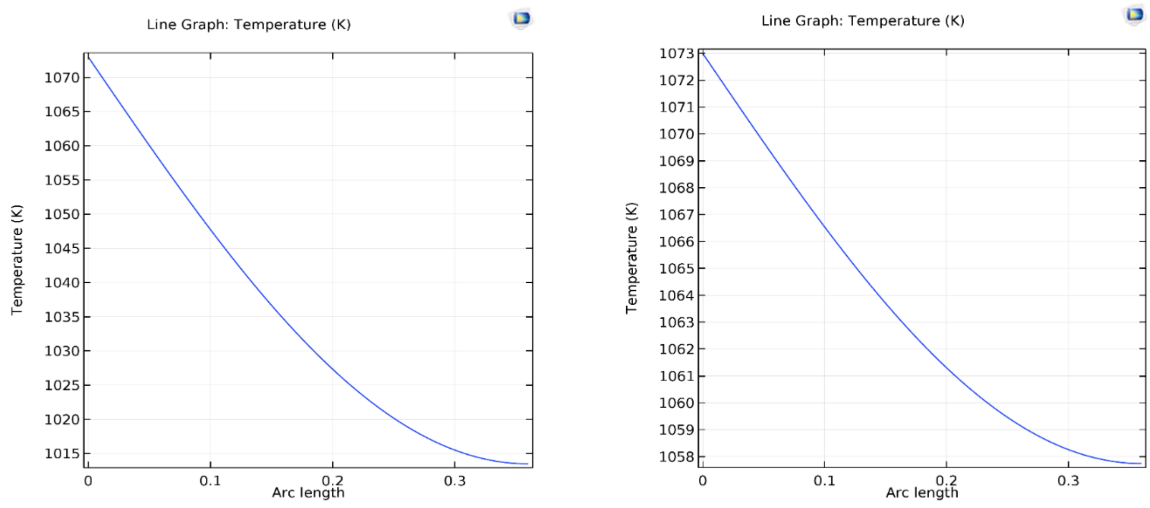
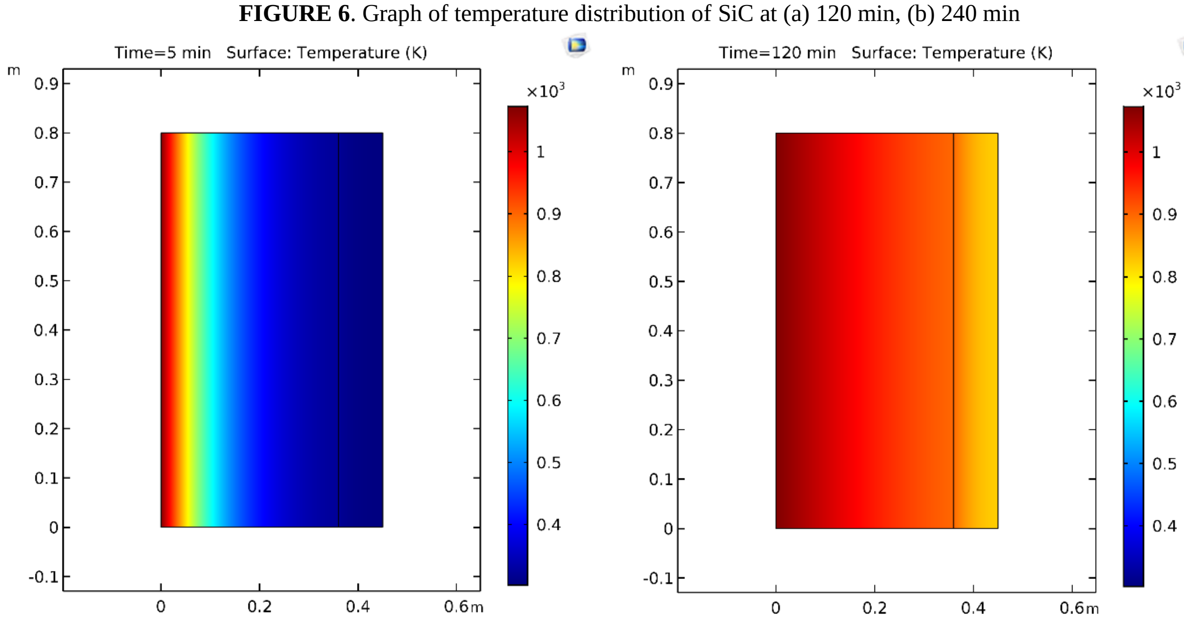



**FIGURE 5.** Temperature distribution of SiC during 120 min




(a) (b)

**FIGURE 6**. Graph of temperature distribution of SiC at (a) 120 min, (b) 240 min




(a) (b)

**FIGURE 7**. Temperature distribution of SiC with corundum at (a) 5 min, (b) 120 min

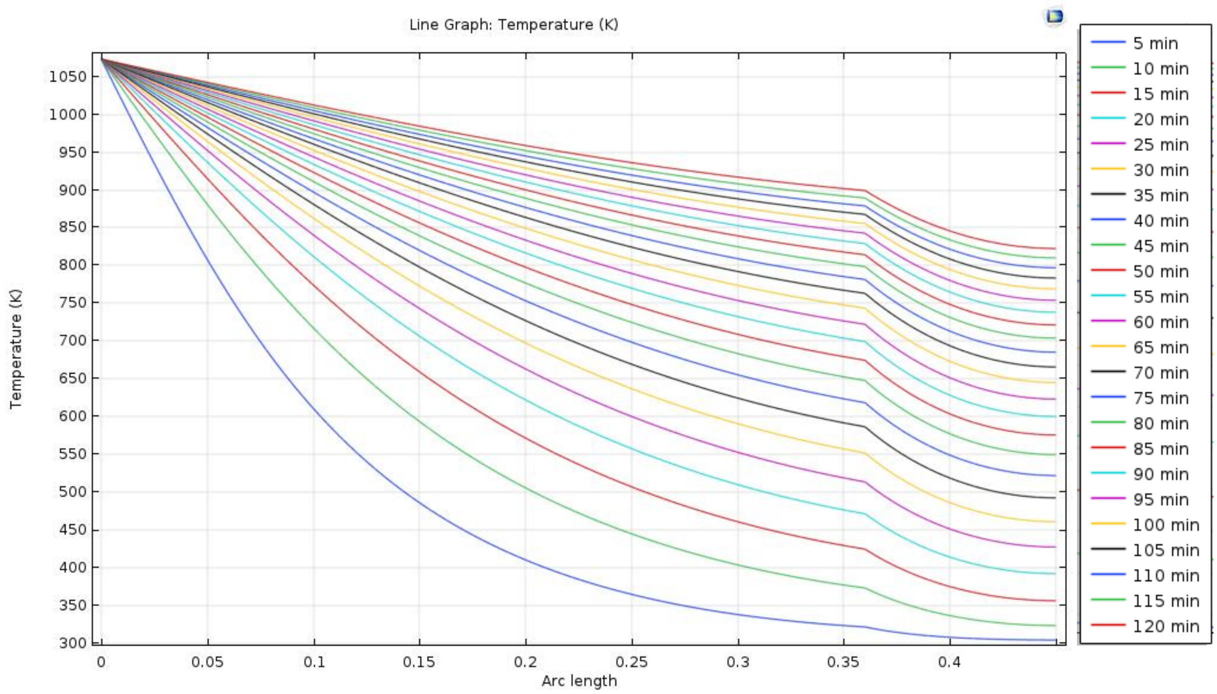



**FIGURE 8.** Temperature distribution of SiC with corundum during 120 min

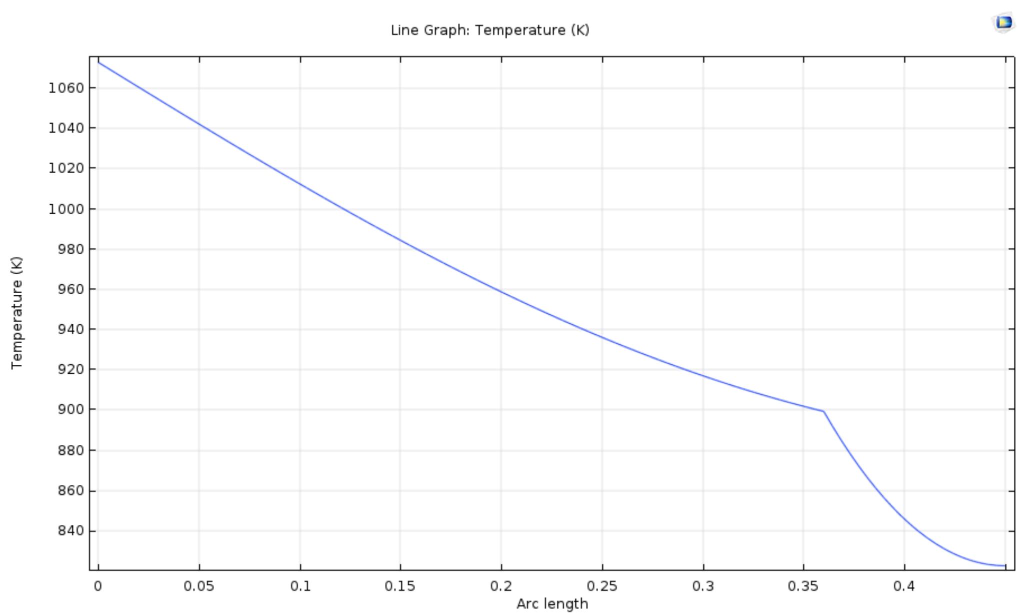



**FIGURE 9**. Graph of temperature distribution of SiC with corundum at 120 min

Comparison of two conditions simulation above, the first heat transfer simulation on SiC without corundum and second simulation of heat transfers on SiC with corundum thickness of 9 cm to show the relationship between temperature change and time for 120 min at the thickness of each simulation. Comparison is made by dividing the temperature at the end of the thickness SiC without corundum and SiC with corundum by the initial temperature at each time.

**TABLE 2**. Comparison of Temperature at Right Side with Temperature at Left Side of SiC and $Al_2O_3$

| Corundum | Time (minute) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **t=5** | **t=10** | **t=20** | **t=30** | **t=40** | **t=50** | **t=60** | **t=70** | **t=80** | **t=90** | **t=100** | **t=110** | **t=120** |
| 0 | 0.31 | 0.39 | 0.52 | 0.62 | 0.69 | 0.76 | 0.80 | 0.84 | 0.87 | 0.90 | 0.92 | 0.93 | 0.94 |
| 9 cm | 0.28 | 0.30 | 0.37 | 0.43 | 0.49 | 0.54 | 0.58 | 0.62 | 0.66 | 0.69 | 0.72 | 0.74 | 0.77 |

Table 2 shows that the longer the heating time, the greater the value of the temperature ratio between the end of the thickness and the temperature of the initial point. This is present that a longer time exhibits good heat transfer along the thickness of the slab. The second information that we can get conditions with an increase in the corundum layer on SiC will reduce the ability to transfer heat in the same period of time.

The result of temperature at tip of SiC thickness (x = 36 cm) for the two simulation conditions shows in Table 3. It can be seen that at the same time for the same position (x = 36 cm), there is a temperature difference in SiC conditions without and with corundum. The SiC condition without corundum for the whole time has a higher temperature value compared to the condition with corundum. This is due to heat transfer with a conduction mechanism where the atoms will move in order to distribute heat, the presence of corundum with a certain thickness affects the movement of SiC atoms from the initial position to the final position. So that at the same point, x = 36 cm, there is a temperature difference.

**TABLE 3**. Comparison of temperature at tip SiC Thickness (x=36 cm)

| Time (t) | Temperature at x = 36 cm (K) | |
|---|---|---|
| **(minute)** | **SiC** | **SiC + $Al_2O_3$** |
| 10 | 416 | 374 |
| 20 | 557 | 472 |
| 30 | 664 | 552 |
| 40 | 746 | 619 |
| 50 | 811 | 675 |
| 60 | 862 | 723 |
| 70 | 902 | 764 |
| 80 | 935 | 799 |
| 90 | 962 | 830 |
| 100 | 983 | 857 |
| 110 | 1000 | 881 |
| 120 | 1013 | 902 |

## CONCLUSIONS

Based on the simulation, the presence of corundum $Al_2O_3$ will inhibit the heat transfer provided by the furnace for melting aluminum with a SiC slab. When 9 cm thickness of corundum was added to the slab, the heat was not sufficient to melt the aluminum due to the presence of an inhibitor in the form of corundum ($Al_2O_3$). It can be concluded that the presence of corundum inhibits the effectiveness of heat transfer. In the future, simulations with various thickness and geometry conditions for refractory will be carried out to obtain a more effective and standardized heat transfer so that energy and cost-effectiveness can be obtained in the aluminum production process.

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